DUAL-MODE CHEMICAL-ELECTRIC THRUSTERS FOR SPACECRAFT

CROSS-REFERENCE TO RELATED APPLICATION

The current application claims priority on U.S. Provisional Application No. 60/423,241, filed November 1, 2002, the disclosure of which is incorporated herein by reference.

STATEMENT OF FEDERAL FUNDING

The federal government may have rights under this application pursuant to funding provided under Air Force Grant No. F04611-00-C-0036.

FIELD OF INVENTION

The invention relates to the field of spacecraft propulsion, and more specifically to propulsion systems for spacecraft with mission requirements for both high thrust and high specific impulse propulsion capabilities.

BACKGROUND OF THE INVENTION

Spacecraft propulsion generally falls into two classes – chemical and electric. Chemical propulsion thrusters (solid motors, liquid engines, or hybrids) have high thrust, which translates to fast maneuverability and short transit times at the expense of using a relatively large mass of propellant. Electric propulsion (EP) thrusters have high exhaust velocity and low thrust. EP thrusters have the advantage of using about 1/10th the propellant mass at the expense of relatively long transit times. The EP systems also provide a smaller impulse-bit than the chemical propulsion systems making them better suited for fine positioning spacecraft maneuvers.

In general it would seem that a spacecraft designer would always choose the EP system to take advantage of the propellant mass savings, however, for many spacecraft maneuvers the longer trip times of the EP system are unacceptable. In general EP is used for maneuvers where trip time is not an issue. These include north-south station-keeping (NSSK) for geosynchronous (GEO) satellites, east-west station-keeping (EWSK), attitude control, and drag make-up in low earth orbits (LEO). In contrast, chemical systems are

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used in applications such as orbit transfer, divert propulsion on interceptor satellites used in missile defense, and proximity operations for microsatellites performing maneuvers near other space objects, where time is of an essence.

To overcome the inherent disadvantages of both propulsion systems, it is common in spacecraft design to include multiple propulsion systems to independently provide high thrust and high exhaust velocity capability. For example, a Boeing 702 communications satellite contains two independent propulsion systems; a chemical rocket is used for a rapid orbit transfer from low orbit to a position near the final geosynchronous orbit, while an EP system is used to complete the orbit transfer using less propellant mass than the chemical rocket would have used. Once in a geosynchronous orbit the EP thrusters move to face north and south. For the 15 year lifetime of the satellite they will be fired for about 1 hour/week to perform NSSK orbit corrections.

One prospective example of the need for multiple propulsion systems on satellites is for use on microsatellites. One microsatellite mission is to act as a defensive escort for a high-value space asset such as the International Space Station, or an expensive communications satellite. These escort satellites would need EP to fly near the host satellite while consuming a minimum of propellant, however, if a threat to the host appears, the escort microsatellite will need high thrust chemical propulsion to quickly respond and intercept the threat. Alternatively, if a microsatellite was designed for inspection missions the microsatellite would need EP for precision pointing and drag make-up, however, near the target the microsatellite will need high-thrust chemical propulsion to circumnavigate the object at close range.

Despite the clear need for a multiple mode propulsion system, such systems are are inherently complex because of the need for multiple control systems and fuel sources. There are currently no propulsion systems that can operate in a chemical or electric mode using the same propellant for the two modes of operation.

Accordingly, a need exists for a propulsion system having both high thrust and high specific impulse propulsion capabilities

SUMMARY OF THE INVENTION

The current invention is directed to a propulsion system that can operate in either a high-thrust-mode (chemical) or a high-exhaust-velocity mode (electric) on command using a single common source of propellant. The propulsion system combines methods for controlling the ignition, combustion rate, and extinguishment of a solid motor using an Electrically Controlled Extinguishable Solid Propellant (ECESP) and a solid propellant motor that uses such a material and is controlled by the application and removal of electrical current, and additionally the use of these ECESP propellants in an electric propulsion device known as the Pulsed Plasma.

There are currently no propulsion systems that can operate in a chemical or electric mode using the same propellant for the two modes of operation.

In one exemplary embodiment the invention is directed to a dual mode spacecraft thruster where electrodes embedded in the exhaust nozzle provide additional electrical acceleration to the exhaust of a chemical rocket motor.

In another exemplary embodiment the invention is directed to a dual mode spacecraft thruster where the solid motor combustion is controlled by the application of electricity.

In still another exemplary embodiment the invention is directed to a dual mode spacecraft thruster where the electrical energy to the nozzle electrodes is provided by an intermediate energy storage device such as a capacitor.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be better understood by reference to the following detailed description when considered in conjunction with the accompanying drawing wherein:

Figure 1 shows a somewhat schematic diagram of an exemplary embodiment of a dual mode chemical-electric thruster according to one embodiment of the invention.

Figure 2 shows a somewhat schematic diagram of an exemplary embodiment of a dual mode chemical-electric thruster according to one embodiment of the invention during a high thrust operation.

Figure 3 shows a somewhat schematic diagram of an exemplary embodiment of a dual mode chemical-electric thruster according to one embodiment of the invention during a high exhaust velocity operation.

DETAILED DESCRIPTION OF INVENTION

The current invention is directed to a propulsion system that can operate in either a high-thrust-mode (chemical) or a high-exhaust-velocity mode (electric) on command using a single common source of propellant. Accordingly, the current propulsion system replaces the multiple chemical and electric propulsion systems with a single propulsion system thereby reducing mass, cost and complexity.

Using a common propellant for the chemical and electric propulsion allows the spacecraft significant orbit flexibility. For example, using the example of the escort satellite, if no requirement (i.e. threat) appears for the high thrust chemical thruster, all of the propellant can be used in the EP thruster thereby increasing lifetime. Using the case of the LEO-GEO orbit transfer, the customer can choose after launch how much of the propellant to allocate to high-thrust (decreasing trip time), and how much propellant to allocate to high exhaust velocity of EP (decreasing propellant consumption).

A schematic diagram of an embodiment of the dual-mode chemical electric thruster in accordance with the current invention is shown in Figure 1. As shown, in one embodiment, the thruster **10** consists of a solid motor casing **12** of any suitable design containing a formulation of the electrically-controlled extinguishable solid propellants (ECESPs) **14** disclosed by Katzakian et al (U.S. Prov. App. No. 60/287,799, filed on April 30 2001), the disclosure of which is incorporated herein by reference. At the propellant face **16** are two electrodes **18** for applying electric current to the face of the ECESP material **14** so as to control the combustion and burn rate.

Although one electrode design is shown in Figure 1, any suitable electrode arrangement may be utilized with the current invention. For example, several suitable electrode designs and methods are disclosed by Dulligan, et al. (U.S. Patent Application Nos. 10/342,003, and 10/342,718), the disclosures of which are incorporated herein by reference. Current is applied to the electrodes **18** by the power processing unit (PPU) **20**, which converts the spacecraft bus power **22** to the voltage and current waveform needed

to energize the ECESP propellant **14**. To direct the thrust produced by the propulsion system **10** the front of the chemical motor is a rocket nozzle **24** of traditional design. Embedded in the nozzle is an additional set of electrodes **26** used to electrically accelerate the exhaust propellant to a high exhaust velocity. A capacitor **28** is attached to the electric electrodes for energy storage. A DC-DC converter **30** is used to charge the energy storage capacitor. The DC-DC converter in turn is charged on command by the PPU **20**.

The thruster device of the current invention is thus able to electrically control the combustion of a solid propellant. This enables very fast ignition and extinguishment of the solid propellant, and thereby enables the device to combust a very small amount of mass. This is of principal importance in the operation the thruster in the electric high exhaust velocity mode. In such a mode, to electrically accelerate the combustion products to high velocity, the capacitor must supply energy sufficient to the mass of the object according to the equation mv^2, where m is the mass to be accelerated and v is the exhaust velocity. The energy available for electric acceleration is realistically limited to less than about 100 Joules by capacitor mass and technology. Therefore the mass to be accelerated must be kept to extremely low levels (<100 micrograms) for the electrical acceleration to be effective. If the mass created in the propellant combustion is too high, the available capacitor energy will only provide a partial acceleration, and increases in exhaust velocity will quickly become negligible.

Although the above discussion has focused on those portions of the thruster that provide ignition and propulsion, it should be understood that the dual-mode thruster of the current invention may also include supporting mechanical and electronic devices. For example, the dual-mode thruster may include a programmable or hardwired control system to provide a means for the thruster to switch between the high thrust and high exhaust velocity modes of propulsion.

In addition, although the above discussion has focused on the design of the thruster itself, the current invention is also directed to a method of propelling a satellite using the thruster. As discussed above, a thruster designed in accordance with the current invention may be operated in two different mode, either a high thrust mode (analogous to a conventional chemical thruster), or a high exhaust velocity mode (analogous to a

conventional electrical propulsion system). The difference in operation of the propulsion system is shown schematically in Figures 2 and 3.

As shown in figure 2, during high thrust operation, the PPU **20** applies a current and voltage to the electrodes **18** at the face **16** of the ECESP propellant **14**. The applied electrical current causes the propellant to initiate combustion **32**. Propellant combustion creates a high-pressure gas **33** within the combustion chamber **34**, which exhausts through the nozzle **24** to create high thrust in the conventional manner for solid rocket motors. In such an operational mode the propellant combustion and thrust production continues until the electrical power from the PPU is commanded off by the user. For the high thrust case the PPU does not charge the capacitor. For a properly optimized propellant, motor, and electrical circuit the device will produced exhaust velocities in the range of about 2500 m/s to 3000 m/s.

Operation of the device in the high exhaust velocity mode starts with the PPU **20** charging **36** the capacitor **28** to some predetermined energy and voltage level. Once the capacitor is charged the PPU switches to energize the electrodes **18** at the face of the ECESP propellant **16**. In this case the PPU produces a pulse of electrical current **38** across the propellant face so as to liberate a very small mass of the propellant **40**. This vaporized mass exhausts, at relatively low velocity, into the nozzle **24**. Once in the nozzle, the exhaust gas makes contact with the electric electrodes **26**, currently at high voltage from the capacitor pre-charging. The voltage on the electrodes, coupled with the partial ionization of the exhaust products, is sufficient to initiate a gas discharge arc **42** in the exhaust. This discharge arc further ionizes the gas and accelerates it using primarily electromagnetic forces. Specifically, electrical current through the gas interacts with the magnetic field, also created by those currents, to create a Lorentz force ($F = J \times B$) directed out of the thruster exhaust plane. The electromagnetic acceleration is much greater than the thermal acceleration of the chemical rocket. For properly chosen electrical parameters and geometry, the device operated in the electrical mode will produce exhaust velocities in the range of about 10,000 – 30,000 km/s.

Regardless of the specific design, the propulsion system at its foundation combines methods for controlling the ignition, combustion rate, and extinguishment of a solid motor using an Electrically Controlled Extinguishable Solid Propellant (ECESP)

and a solid propellant motor that uses such a material and is controlled by the application and removal of electrical current, and additionally the use of these ECESP propellants in an electric propulsion device known as the Pulsed Plasma.

Accordingly, although specific embodiments are disclosed herein, it is expected that persons skilled in the art can and will design alternative dual-mode propulsion systems and methods that are within the scope of the following claims either literally or under the Doctrine of Equivalents.